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RECENT AND FUTURE ENHANCEMENTS IN NDI FOR AIRCRAFT STRUCTURES (POSTPRINT)

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Abstract. The U.S. Air Force's (USAF) Aircraft Structural Integrity Program (ASIP) was established in November 1958 in response to in-flight structural failures. Additional failures in the late 1960's, far short of the qualified safe-life, demonstrated that the safe-life approach had shortcomings. The USAF implemented a damage tolerance approach in response to these failures, recognizing that an aircraft's structure has a wide range of initial quality from manufacturing processes plus service induced damage and that the aircraft structure had to be inspectable. The results of the damage tolerance assessments were incorporated into USAF Technical Orders which established inspection and maintenance requirements to maintain structural integrity and to control risk to an acceptable level. Therefore, the execution of effective nondestructive inspection (NDI) is essential to maintain the structural integrity of USAF aircraft and clear guidance is provided in the ASIP standard. This requires new inspection technology to be evaluated to ensure that the inspections are reliable and repeatable when performed by the typical field or depot level inspectors.

Active research and development (R&D) at the Air Force Research Laboratory (AFRL) has resulted in new NDI technical enhancements and technology to address the need for improved tools to assess structural integrity of structures while continually striving to reduce the time and resources to accomplish NDI of aircraft structure. This includes improved eddy current probes, improved eddy current instrumentation, as well as other electromagnetic and ultrasonic-based capabilities. These technology improvements are described together with the processes to perform the validation/verification of these technologies and USAF processes that are in place to maintain uniform capability for all NDI inspections regardless if they are performed in a field or depot environment. In addition, current R&D initiatives are reviewed including applications and objectives of the capability being developed. Lastly, future research initiatives for materials and structural NDI methods are discussed.

Introduction

The U.S. Air Force's ASIP was established in November 1958 in response to in-flight structural failures resulting in five destroyed B-47 aircraft from March through April 1958 [1]. Four of the B-47 losses were attributed to fatigue, which led to a probabilistic approach for establishing the aircraft service life capability. This was called the "safe life" approach, and it relied upon the results of a laboratory test of a full-scale airframe subjected to loading that simulated the operational service environment of the aircraft. The USAF



established the safe-life of the aircraft by dividing the number of successfully test simulated flight hours by a scatter factor. The intent of the factor was to account for aircraft-to-aircraft variation in materials and manufacturing quality. The USAF believed the process to be sufficient to preclude in-service structural failures attributable to fatigue. The safe-life approach was the basis for all new designs during the 1960s and was also used to establish the safe-life of earlier designs that were subjected to a fatigue test.

Losses of an F-111 in December 1969 and an F-5 in April 1970 [1], each far short of their qualified safe-life, demonstrated that the safe-life approach had shortcomings. The safe-life approach allowed the use of low ductility materials operating at high stresses, which resulted in designs that were intolerant to manufacturing and service-induced defects. The aircraft failures arising from the deficiencies of the safe-life approach demanded a fundamental change be made in the design, qualification, and inspection of aircraft. The damage tolerance approach emerged as the candidate chosen for this change.

Developers of the damage tolerance approach recognized that an aircraft's structure is subject to a wide range of initial quality from manufacturing processes as well as from service induced damage. They also recognized that the aircraft structure had to be inspectable. To ensure the aircraft operates safely in the presence of anomalies, the USAF requires the structure to tolerate defects for some inspection-free period of service usage. The damage tolerance approach provides the USAF a safety limit for each critical area in the aircraft. The safety limit is the time, in flight hours, required for a crack to grow from either an assumed initial flaw size, or the inspectable flaw size, to a critical size. Inspections are scheduled to occur at a time equal to one-half the determined safety limit. The USAF used the damage tolerance approach to upgrade the structural integrity of several operational aircraft in the early 1970s including the F-111, C-5A and F-4. The success of these endeavors convinced the USAF that damage tolerance should be the structural safety basis for all future designs. In December 1975, the USAF formally integrated the damage tolerance approach into the ASIP.

During the 1970s and 1980s, the USAF performed a damage tolerance assessment on every major aircraft weapon system to develop inspection or modification programs necessary to maintain operational safety [2]. The results of the damage tolerance assessments were incorporated into USAF Technical Orders (TO) which established maintenance requirements to maintain structural integrity and to control risk to an acceptable level. As a measure of success for aircraft designed and/or maintained using a damage tolerance approach, the USAF destroyed aircraft rate due to structural reasons is between one and two destroyed aircraft per ten million flight hours accumulated in the fleet. This is at least ten times lower than the overall USAF destroyed aircraft rate due to all causes except combat related. Accordingly, the USAF believes the damage tolerance approach incorporated into the ASIP in the 1970s continues to be the cornerstone for protecting the safety of the USAF fleet.

1.0 Role of NDI within ASIP

The effectiveness of any military force depends, in part, on the safety and operational readiness of its weapon systems. One major item of an aircraft system that affects its operational readiness is the condition of the aircraft structure. The aircraft structure capabilities, condition, and operational limitations must be established to maintain operational readiness. Potential structural or material problems must be identified early in the life cycle to minimize their impact on the operational force. In addition, a preventive maintenance program must be developed and implemented for orderly scheduling of inspections, replacements, or repairs of life-limited elements of the aircraft structure. The overall program to provide USAF aircraft with the required aircraft structural

characteristics is referred to as the Aircraft Structural Integrity Program, or ASIP. The goal of ASIP is to ensure the desired level of structural safety, performance, durability, and supportability with the least possible economic burden throughout the aircraft's service life.

The objectives of the ASIP are to:

1. Define the structural integrity requirements necessary to support airworthiness assurance and the program manager's assurance of operational safety, suitability, and effectiveness;
2. Establish, evaluate, substantiate, and certify the structural integrity of aircraft structures;
3. Acquire, evaluate, and apply usage and maintenance data to ensure the continued structural integrity of operational aircraft;
4. Provide quantitative information for decisions on force structure planning, inspection, modification priorities, risk management, expected life cycle costs, and related operational and support issues;
5. Provide a basis to improve structural criteria and methods of design, manufacturing, evaluation, and substantiation for future aircraft systems and modifications.

To achieve this goal and these objectives, ASIP consists of a series of five interrelated tasks as defined in MIL STD 1530C. Although these tasks have evolved over the years, they have had essentially the same focus since its inception. The first four tasks are primarily associated with aircraft development, while the last task occurs during an aircraft's operational life until it is retired [3]. Thus, the five ASIP tasks span the entire life cycle of an aircraft, from conceptual design to retirement and NDI is integral to each task.

The first task develops the criteria that must be applied during design to ensure overall program requirements will be met and includes establishing the NDI program and an NDI Requirements Review Board (NDIRRB) to implement appropriate NDI process into all phases of the program. The second task focuses on operational environment characterization, plus initial testing of materials, components, and assemblies. Analysis includes ensuring design meets requirements. NDI capability for process monitoring and quality control is assessed with emphasis on fracture and/or mission critical structural parts.

The third task addresses full scale durability testing and includes NDI as an integral component to detect damage as early as possible, provide estimates of crack size, and minimize risk of catastrophic failure. Task IV focuses on the analysis that leads to certification of the aircraft structure and the processes/procedures used for force operations. For NDI, this includes the selection of the method as a function of material, geometry, accessibility, and human factors. The resulting assumed detectable flaw size requires approval by the NDIRRB. The NDI methods and capabilities are documented in the force structural maintenance plan (FSMP) and appropriate TOs for execution.

The fifth task addresses once an aircraft is placed in use and includes the execution of NDI required by the FSMP. In many cases, NDI requirements evolve during this phase due to mission and usage changes, modifications, updated analyses, additional testing, damage discovered during maintenance, quantitative risk analysis, and service life extensions. In addition, NDI is an integral part of the surveillance program which includes the analytical condition inspection (ACI) conducted throughout the life of the aircraft and the structural teardown program conducted on as needed basis

2.0 Recent USAF NDI Concerns and Corrective Actions

Concerns regarding the capabilities of standardized USAF inspections arose in the mid-2000s with the discovery of cracks being missed during inspections established by ASIP. This led to a comprehensive review of how inspection processes were being executed and a program to improve the accomplishment of required inspections [4]. The program focused

on both procedures and potential of applying and/or developing technology to address shortfalls. The procedures, or Technical Orders (TOs), for performing inspection were often found to be based on outdated processes using obsolete equipment. While shortfalls had been recognized, the impact of these shortfalls was not clearly and quantitatively assessed until this program.

To address the concern that some ASIP inspection were not being accomplished as intended, the program reviewed over 220 inspections for the USAF fleet using input from the ASIP Managers for each weapon system to prioritize procedures that required review. The review analyzed the procedures to determine if the TO clearly indicated the location to be inspected, properly identified the inspection process to use, and/or provided the correct level of guidance for any scanning of the part. Common issues found with the TOs included incorrect references to standard procedures, lack of clarity in describing the region to be inspected via written instructions, and poor graphics to support the written instructions indicating where inspections were to occur. Revisions to the TOs, whether specific to a particular weapon system or part of the general instructions for inspections, were accomplished by the end of calendar year 2010 to rectify these issues [4]. Furthermore, standard method-specific inspection procedures were developed leveraging best industry and DoD practices. Implementation of these procedures in addition to standardizing equipment across the USAF has contributed significantly to an understanding and control of the USAF baseline inspection capability. Two Structures Bulletins were also issued to define the criteria for when a repeated inspection of safety-of-flight structure is necessary and how to properly define safety-of-flight structure and the associated NDI procedure [5]. Most recently, a Structures Bulletin was developed to define best practices for performing formal validation and verification of inspection procedures [6] by NDI Level IIIs to ensure the required detection capability can be achieved.

Parallel to the evaluation of the TOs, an analysis was performed on the assumed capability for ASIP inspections as a function of weapon system. It was found that different capabilities were being used to determine inspection intervals for different aircraft [7]. This led to an internal effort within the USAF to baseline the capability of frequently used inspection procedures as a function of general classes of structural geometric features. This capability was documented in the publication EN-SB-08-012, “Nondestructive Inspection Capability Guidelines for United States Air Force Aircraft Structures,” which is currently in Revision C [8].

The document divides various inspection methods, such as eddy current and fluorescent penetrant, into sections where capability is determined by geometry. Typical aircraft geometry includes raised head fasteners, edges, radii, and flat or open areas, such as those found close to flush head fasteners. The initial publication in 2008 indicated the originally assumed capability for some inspections were often overstated [7]. This led to immediate and accelerated research and development activities at the Air Force Research Laboratory (AFRL). These activities resulted in NDI technical enhancements and technology to improve tools used to assess the integrity of structures while continually striving to reduce the time and resources to accomplish NDI of aircraft structure.

3.0 Recent USAF NDI Enhancements

The accelerated R&D efforts at AFRL to address technology shortfalls include improved eddy current probes, improved eddy current instrumentation, as well as other electromagnetic and ultrasonic-based capabilities. Initial efforts focused on developing improved eddy current capability as this method is used for the majority of USAF ASIP inspections for metallic aircraft. For the four generic classes of geometry listed above, development efforts initially focused on modified hand-held probes to detect cracks. The

primary motivator for these developments was to decrease human factors induced variance for inspectors using conventional eddy current pencil probes. Pencil probes maintain maximum capability only when the coils are kept perpendicular to the surface being inspected. ; Furthermore, scan coverage is difficult to control, particularly in areas where access is challenging.

For raised head fasteners, a probe geometry was developed that included the eddy current coil positioned within a guide that fit over the fastener head much like a socket fits over a bolt head. A representative picture of these probes is shown in the inset of Figure 1a together with a picture showing how this probe would be used on a representative raised head fastener inspection. With this probe, the 90/95 capability to detect surface breaking cracks extending beyond the diameter of the fastener head was improved by 50 percent compared to pencil probes as determined via a probability of detection (POD) study [4, 9].

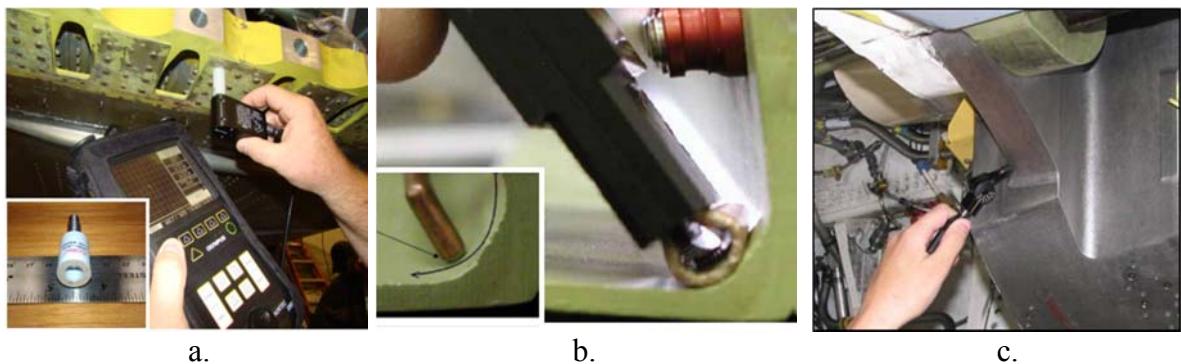


Figure 1. a) Raised head fastener probe used on representative aircraft structure. Inset shows probe with socket-like geometry to fit over a raised head fastener, b) Conformal ribbon probe illustrating its adaptability to the geometry of the radius with varying curvature. Inset shows a pencil probe scanning requirement to cover the same region of interest, c) conforming edge probe being used on a typical aircraft structure.

Another probe set was developed for radii seen in typical aircraft structures. For this class of probes, the eddy current coil is placed in a flexible circuit to allow it to conform to the shape of the radius. Several probes are required to accommodate the different diameters of radii found on most USAF aircraft. Figure 1b shows a comparison between typical applications of a pencil probe with that of the new conformal probe [4]. With this approach, the 90/95 ability to detect axially aligned, surface breaking cracks located in the radii improved by 60 percent when compared to pencil-based probes [8].

A third geometry addresses inspections that occur along an edge. In this case, the eddy coil is mounted in a v-shaped guide that is mounted to a probe holder that includes gimbals to allow the v-shaped guide to follow an edge even as it changes curvature. A representative picture of the probe is shown in Figure 1c [4]. As with the other two probe configurations, this edge probe minimizes awkward probe manipulation, maintains a consistent distance between the coil and the surface being inspected, and accommodates for changes in geometry in the region of interest. Validation of this capability via a POD study indicated an improvement of the 90/95 crack size that can be reliably detected by nearly 70 percent when compared to free-hand scanning with a pencil probe [9]. It is important to note that the capabilities of these new probe technologies were validated using the POD methods described in MIL HDBK 1823A [10].

These next generation eddy current probes are currently being deployed throughout the USAF. The significant advantage of using these new probes is the extension of inspection intervals based on the validated capability to detect smaller cracks. Representative improvements have been documented for the F-16 Fighting Falcon, where for one control point the capability of a conventional pencil probe could not reliably detect the required critical flaw size [11]. With the new conformal eddy current probe, the

inspection capability improved such that the inspection interval could be extended to 600 hours to align with other maintenance work performed during a typical phase inspection. Similar improvements are being realized for other weapon systems as the use of these probes becomes more prevalent within the USAF.

4.0 Near-term USAF NDI Enhancements

Improved NDI is a continuous need for USAF ASIP engineers to increase the time between inspections and to minimize the time and aircraft preparation and reassembly to perform inspections. A recent application of the conformal eddy current probe concept was implemented for a bulkhead radius geometry that included blend repairs. This required an additional level of gimbaling to enable the eddy current coil to remain in continuous contact with the region of interest. Of particular interest was how the POD experiment replicated the inspection on the aircraft to precisely simulate access and human factors induced variance [11].

Another development that is approaching readiness for use is a surface scanner to address the detection of fatigue cracks emanating from under flush head fasteners. The scanner includes an eddy current coil mounted to a rotating puck to ensure that the area around the fastener is covered completely by the scanner as it is moved over the region of interest. This includes a visual representation of the area being inspected, including the fastener head and the region around the fastener that could contain a fatigue crack. The scanner and representative output are shown in Figure 2. While the capability has not been validated via POD study, one is planned within the next year to define the sensitivity with the minimum objective that it improves the detection capability over free hand pencil probe inspection by 50% for cracks extending from holes with flush head fasteners installed [9].

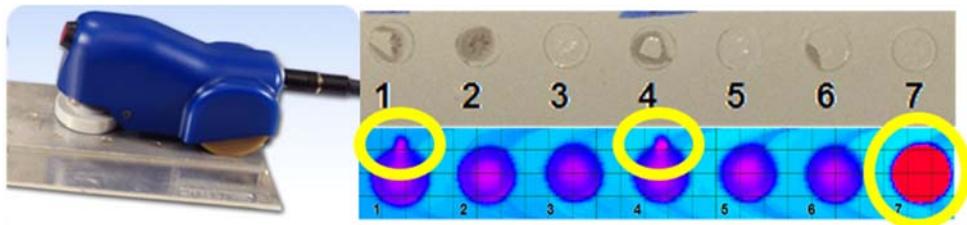


Figure 2. Flush head scanner (left) connected to portable eddy current instrument. Sample (top right) and output: 0.172" crack (middle), 0.142" crack (right) crack under paint, material change in far right fastener.

Rotary bolt-hole eddy current is one of the most sensitive inspection methods available for USAF structures applications, but has the limitation that it does not provide information on which layer(s) contains the crack-like defect(s). A new capability approaching readiness for validation is an eddy current scanning tool to map a hole surface and identify the layer and material in which the crack is located. This capability will eliminate the need to disassemble a component to determine if the crack is located in critical structure, or is located in structure that does not carry load, such as a shim (Figure 3) [12].

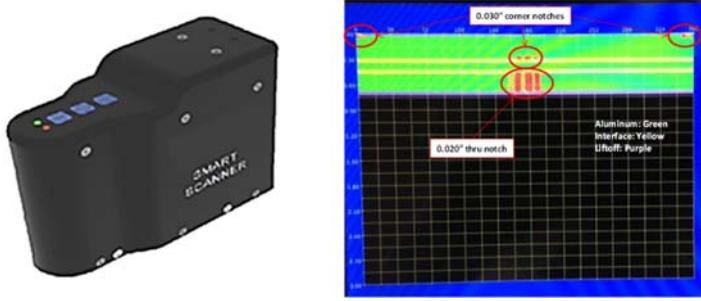


Figure 3. Advance bolt-hole eddy current scanner.

5.0 Future USAF NDI Enhancements

In a slightly longer view, the next iteration of NDI capability will enable the inspection of multi-layered structure without requiring the removal of fasteners. The enabling technology is giant magnetoresistive (GMR) sensors and model-driven methods to tailor the sensor configuration to maximize its sensitivity to fatigue cracks while minimizing other confounding factors, such as sub-surface edges, that can inhibit the accurate detection of cracks. In addition, robotic-assisted inspection capabilities are being explored to develop methods to access hard to reach areas in substructure that cannot be inspected by sensors from the outer mold line of an aircraft. These robotic methods include flexible arms that can be manipulated around substructure and through access holes to place inspection sensors, such as eddy current probes, accurately to the region of interest.

Significantly longer range research is underway at AFRL to develop NDI-based methods to characterize damage in aircraft structure. For fatigue cracks, this includes the location and the size of the crack with statistical metrics of accuracy so this information can be used for risk analysis. In addition, accurate knowledge of the size of damage can assist in the rapid maintenance decisions that are required to return the aircraft to service without relying on the current iterative processes that can be extremely time consuming and costly. Included in this work is defining the needs for capturing data acquired by inspection systems, determining the location and configuration where inspections are performed, plus developing the algorithms to use this data to determine the defect size. As there are many factors that influence the response from an inspection in addition to the presence of the defect, model-based methods are being used to develop the inversion process and applied mathematics are being explored to quantify the accuracy of the size determination.

Similar work is being initiated to address the needs to characterize damage in composite structures as inputs to damage growth models. This will enable the management of the integrity of composite structures to migrate from the current event-driven life management to a damage tolerance approach similar to the current USAF method to ensure the integrity of metallic structure. Much of this work focuses on ultrasonic methods and includes advanced methods for using phased array capability to characterize the area and depth of composite damage, such as typical damage from an impact or other related event.

6.0 Summary

The USAF ASIP uses a damage tolerance approach to ensure the safety of aircraft structures. This approach evolved from experience in addressing shortfalls in other approaches to mitigate risk of structural failures due to production and/or service induced damage. Periodic inspection using NDI methods is a key component of this approach, as the validated capability of the NDI technique determines the inspection intervals and the

POD curve for the inspections is an input to risk calculations. Detected fatigue cracks require remediation to ensure safety of aircraft is maintained within acceptable risk levels.

Concerns regarding the USAF capability of aircraft inspection led to several parallel efforts to ensure a standardized capability existed for all field and depot locations where NDI is accomplished. Many issues could be addressed by improving the content and clarity of the TO instructions used to accomplish NDI as intended. Additional processes include the review of new procedures on aircraft before they are released as a TO.

Shortfalls in capability were addressed with new technology. This includes conformal eddy current probes to improve the sensitivity and facilitate the execution of surface inspections for fatigue cracks in four classes of aircraft structure geometry: flat surfaces, edges, radii, and raised head fasteners. These probes have been validated and standardized capabilities to detect fatigue cracks have been quantified and shown to be significantly better than current pencil probes in many cases. Additional technology development is in process to address inspection for fatigue cracks around flush head fasteners and for determining the layer in which fatigue cracks are located when performing bolt-hole eddy current. Future technology development includes addressing multi-layered structures without disassembly, improved access to internal structures using robotics, and ultimately sizing defects with statistical metrics to improve fleet management options when damage is found and to accelerate disposition of any discovered damage.

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